STRATEGIES FOR TAILORING RELIABILITY TEST STANDARDS[1]

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BIOGRAPHY

The author has actively participated in spacecraft and payload development since the establishment of NASA. He was instrumental in the development of early engineering mechanics space technologies, particularly in spacecraft temperature control and STV testing. During 37 years at JPL, he was the principal investigator for three flight engineering research experiments, managed three small projects including a $50M Spacelab experiment, served twice as a program manager, and represented JPL in Headquarters and intercenter management activities related to STS and Space Station payload integration and test. Don Lewis is currently supervising a group which helps flight projects with product assurance planning and is leading an assessment of JPL and NASA product assurance programs.

ABSTRACT

The paper suggests a simple strategy for the tailoring of the ground testing of unmanned spacecraft including considerations of project costs and risks. It is simply stated in five steps: (1) access the specific project's requirements and constraints, (2) use the existing comprehensive quality assurance programs as a guide, (3) prioritize the risks, (4) prioritize the tests, and (5) tailor the test program as appropriate. This approach addresses the specific project needs without unduly compromising the wealth of accumulated flight experience. Tailoring falls into three categories; tailoring of test levels, tailoring of test configurations, and tailoring of test techniques. Three examples are included to illustrate these types of tailoring activities. This paper on strategies for tailoring spacecraft test standards both advocates for and cautions against tailoring depending on the situation. Applied sensibly and carefully, tailoring can improve the test effectiveness and relax constraints on certain project resources. On the other hand, tailoring a product assurance program usually incurres some element of risk and may increase project costs.

KEYWORDS

Tailoring, Test, Product Assurance, Reliability, Costs, Risk, Strategy, Standards

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Introduction - Design and spaceflight experience has accumulated over the last three decades in an environment of "success at any cost." This has resulted in a comprehensive NASA product assurance program. This experience has been partly captured in standards, preferred procedures, lessons learned, and like documentation. In the current environment where "success at any cost" has been replaced with "do the best you can within the resources available," there is an acute need to know how to select a subset of the most important elements from the comprehensive program to meet the needs of specific projects. This selection process and the custom structuring of a reliability test program for each project are, for the purpose of this paper, defined as tailoring. The paper will suggest a simple strategy for the tailoring of the ground testing of unmanned spacecraft including considerations of project costs and risks.

The Strategy - The suggested strategy is simply stated in five steps; most of the discussion will deal with how to take them. The steps are: (1) access the specific project's requirements and constraints, (2) use the existing comprehensive quality assurance programs as a guide, (3) prioritize the risks, (4) prioritize the tests, and (5) tailor the test program as appropriate. This approach addresses the specific project needs without unduly compromising the wealth of accumulated flight experience.

Step (1) - Access Project's Requirements and Constraints

Project resources include available skills, facilities, funds, schedule time, and the like. Schedule time, not cost, is usually the most critical resource limiting the scope of a test program, as will be discussed later. In the typical development schedule, most of the available time is used to select contractors, and to

[1] This paper is based on research conducted at the Jet Propulsion Laboratory, Pasadena, California, sponsored by the NASA Quality Management (Payloads) Division of the Office of Safety and Mission Assurance

design, procure parts, and fabricate the items to be tested. Schedule delays during the development of a spacecraft may shorten the available time remaining before launch with a resulting reduction in the scope of the test program. Sometimes important flight modes are left unverified.

The design of the spacecraft often dictates the complexity and scope of the test program. Sometimes a spacecraft design can be configured without excessive compromise to make it more testable. An old guideline, still valid, is to "make little things mean almost nothing," by selecting a few controllable parameters and make them dominant. For example, a thermal design might make a predictable internal radiation heat exchange dominant over a large number of uncertain heat conduction paths across mechanical interfaces. Or the spacecraft, as in the Galileo, might be mostly shaded from a variable solar heat input and the temperatures forced instead to depend on known and measurable internal power dissipation.

Other design considerations include system redundancies for more work around options in flight, conservative use of previously qualified hardware, and adequate weight, power, memory, and expendables margins. While these precautions may seem obvious, they can literally be worth their weight in gold in the reduction of test costs, in the building of design confidence, and most important in conducting a successful mission.

Whatever design evolves, the test program should address the issues associated with it specifically. What features are new or unfamiliar? Who is going to develop the hardware and under what physical and/or contractual conditions? Is there previous experience with the design or its component elements? Which, if any, standard practices directly apply or to what extent should they be altered? What are the project's priorities and constraints?

These and similar questions form the basis for the development of a product assurance test plan. Guidelines, standard practices, lessons learned lists, and the plans of similar project developments are helpful as background and checklists to assure all aspects of the design are considered.

Step (2) - Use Existing Quality Program As A Guide

The wealth of spaceflight experience accumulated through the years has been expensive and sometimes painful to obtain. It would not be accurate to claim that it has been captured completely in NASA documentation. The formal product assurance documentation tends to emphasize electronic and software disciplines more than electromechanical, optical, or chemical systems. Whether formally or informally documented the experiences of the past should be used as a tutor wherever possible.

In tailor-making a product assurance program, some items in the comprehensive standard programs clearly will not apply. For example, a thermal-vacuum test for a instrument used in a crew compartment would be irrelevant; conversely a crew noise-level test would be inappropriate for an unmanned spacecraft. However, most standard tests are there for a purpose and it is essential that this purpose be reviewed before it is discarded.

The difficulty is, however, that it is hard to separate the cause and effect of the elements of a comprehensive program because they are often interdependent. Which prelaunch activity was responsible for a trouble free flight? Could some of them have been deleted without changing the outcome? Sometimes it is less expensive in cost and time to "kiss the idol" than to isolate its effect. Hopefully, this is the exception. For the most part the formal requirements can be justified based on developed rationale, and this should be reviewed to see if it applies for the specific design and mission under consideration.

Step (3) - Prioritize The Risks

The effective prioritization of risks is more a product of experienced judgement than a quantitative comparison. Historically, prioritization has not been a critical issue because resources have been available to work toward reducing all recognized risks. Even so, resources were often misapplied by emphasizing work on relatively minor risk areas at the expense of more critical ones.

Current research at JPL is attempting to quantify the risks (or hazards) to mission success. One interesting finding of these studies is the significant role of non-electronic assemblies such as electromechanical and pyromechanical discrete-action assemblies and continuously running mechanical assemblies. The caution here is to think past the familiar thermal/vac, vibration, and EMI test programs and include zero-g deployment, thermal differential expansion, material compatibilities, and wear in the list of risks to be addressed.

A typical distribution of risks in a Class A interplanetary spacecraft is illustrated in Figure 1[2]. As indicated, the risks associated with the electronic assemblies are typically less than the various types of mechanisms. This figure was taken from unpublished research activity currently underway at JPL which is attempting to identify and quantify the risks in a baseline Class A design.

Much remains to be done in order to quantify risks,

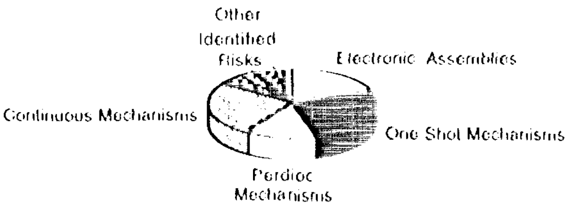

Figure 1, Distribution of Risk in a Typical Class A Spacecraft

but whether done subjectively or quantitatively the idea is to apply the limited resources to the areas of greatest risk while not completely ignoring any of them.

Step (4) Prioritize The Tests

Before discussing the prioritization of tests, the relatively low cost of testing should be addressed. As previously mentioned in Step (1), the most constraining project resource is usually schedule time not costs. An effort is underway at JPL to identify the actual project costs of implementing various elements of the product assurance programs. To adequately discuss these findings would be beyond the scope of this paper, but Table 1 has been included here to illustrate the relatively small costs of testing.

Total project test costs vary considerably due to complexity, development mode, numbers of assemblies tested, and to some extent accounting practices. By looking at the percent of total project cost devoted to environmental testing, the relative size, complexity, and timing of the expenditures can

[2] Definition of Spacecraft Classification are per NASA NMI-8010.1A as reflected in JPL D-1489, Flight Equipment Classification and Product Assurance Requirements, January 1990, or JPL D-8966, Rev. B, JPL Standard for Flight Instrument Classification and Product Assurance Requirements, June 1993.

Project	Developer	Type of Development & Class	Actual Cost $M %	Env Test $M %	I&T $M %	GSE $M %	PA/QA $M %	Total $M %
Galileo (1989)	JPL & Hughes	Spacecraft & Instrument Class A	624 100%	11.1 1.8%	20.8 3.3%	6.1 1.0%	17.3 2.8%	55.3 8.9%
Mars Observer (1992)	MM & GE(RCA)	Spacecraft Only Class A	182 100%	8.3 4.6%	13.2 7.3%	2.5 1.4%	5.1 2.8%	29.1 16.1%
Topex Poseidon (1993)	Fairchild	Spacecraft Only Class B	172	5.3 3.1%	4.9 2.8%	9.5 5.5%	4.1 2.4%	23.8 13.8%
SIR-C (1994)	JPL	Shuttle Instrument Class C	184	2.0 1.1%	2.0 1.1%	3.0 1.7%	3.0 1.7%	10.0 5.6%

Actual Cost = Approx. Development Costs not including Mission Support Costs
Env. Test = Environmental Tests, I&T = Integration & Test, GSE = Ground Support Equipment
PA/QA = Product Assurance and Quality Assurance

Table 1, Product Assurance Test Costs For Selected JPL Projects

be normalized. As shown in column five, the maximum testing cost is less than 5% of the total project development costs and average about half of that percentage. If product assurance, quality assurance, and testing are combined, the average project costs for these four projects is only 5%.

The total costs for a specific environmental test are difficult to isolate. The direct accountable costs for the test set-up, facilities, instrumentation, and test crew do not account for many indirect engineering costs required to support the test. For example, typical in-house JPL costs for various assembly level tests are shown in Figure 2. A minimum cost could be calculated using data of this type multiplied by the

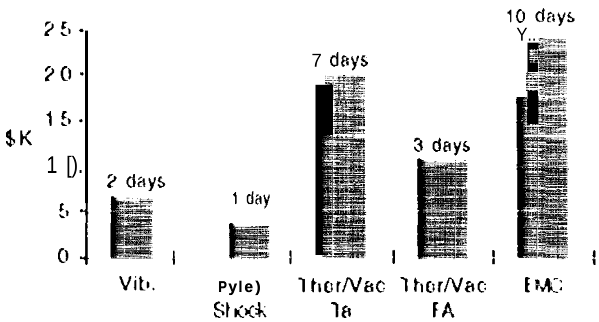

Figure 2, Typical Environmental Test Costs per Item at JPL

number of tests and the number of assemblies for a specific project.

However, this does not account for a larger cost associated with supporting analysts, planners, reviewers, observers, and in absorbing the learning curve for new or inexperienced personnel. The project taxi-meter cost during the system test period may be the most significant of all indirect costs of testing. If the cost of testing is carefully managed it can be kept relatively low. When this occurs, the prioritization of tests becomes less critical.

Even when test costs are held to a minimum there are usually significant schedule constraint on the use of the flight hardware. It may be more beneficial to emphasize one kind of test over another in order to obtain the most confidence with whatever resources are available.

There is a general opinion that the assembly thermal/vac and the system Solar Thermal Vac. (STV) tests are the most important tests based primarily on two observations. First, most problems are discovered in these tests and second, these tests usually best simulate the in-flight conditions. After the thermal/vac tests, the most productive tests have been the dynamic tests. As microcircuits evolve into more compact denser components, EMI tests are becoming increasingly effective in locating problems.[3]

There is flight experience that suggests additional system-level testing may be needed to reduce in-flight failures. Figure 3 is a plot of the cumulative number

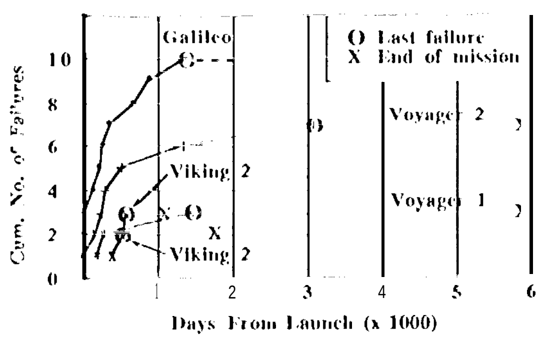

Figure 3, Failure History of Planetary Spacecraft

of flight equipment failures for five JPL interplanetary spacecraft. This and similar flight data for Earth orbiters managed by GSFC,[4] indicate that the failure rates have not leveled off before launch. Additionally, similar data from prelaunch system testing at KSC shows that there is no appreciable change in equipment failure rates at launch.[5]

Launches are certainly traumatic and the vacuum of space does change at least the equipment temperature distribution. As the failure rate pattern continues through the first two to three years of flight the implication of inadequate ground testing is reinforced. Continuation of testing until there is a change in the rate of failures may be a better criteria than specifying a minimum number of operating hours before launch.

Step (5) - Tailor The Test Program As Appropriate

The most appropriate tailoring is that which preserves the maximum applicable accumulated experience yet addresses the particular needs of a specific project. In some, possibly most, cases no tailoring of the standards at all is the most economical and conservative approach. This is because the process of tailoring itself is expensive in both time and engineering.

The developers of low cost instruments at JPL have generated standard documents describing the product assurance requirements. Inserts for each instrument classification are pre-approved and can be physically copied and inserted into the instrument project development plan with a minimum cost.[6]

On larger projects, once the obvious nonapplicable standards are removed from a project product assurance plan, tailoring often falls into three categories; tailoring of levels, tailoring of configurations, and tailoring of test techniques. The following three examples are included to illustrate each of these types of tailoring.[7]

(a) Tailoring of Levels - Typically at JPL, there is goal to keep the junction temperature of semiconductor electronics from exceeding specified levels in flight but to test them at higher temperatures during ground tests in order to accelerate the identification of potential early failures. However, in assemblies where several different kinds

[3] JPL Internal Document D-11295, Rev. A, entitled Environmental Test Effectiveness Analysis Reports, section TETA '1'0-0005 by P. Gonzalez, EMC Testing Significance, April 1992.

[4] M. Krasich, JPL Internal Report, entitled 1< '1 '01" Interim Significant Result (RISER) Report, RISER(16312-01), December 1993.

[5] JPL Internal Document D-11295, Rev. A, entitled Environmental Test Effectiveness Analysis Reports, section TETA '1"0-0016, by C. Gonzalez, Adequacy of Prelaunch Testing Based on Early Flight Anomalies, July 1993.

[6] JPL document D-8966 entitled, JPL Standard for Flight Instrument Classification and Product Assurance Requirements, June 1993.

[7] Examples taken from JPL Internal Document D-11608, Rev A, entitled Guidelines for Tailoring Space Hardware Design and Test, June 1994.

of parts and/or different materials are packaged together there may be incompatibilities of allowable maximum temperatures. To achieve the desired temperature on one component a test may expose another component to an excessively high temperature.

A tailoring technique has been developed which reduces the maximum test temperature level but extends the test time in accordance with an Arrhenius relationship based on chemical reaction rates.[8] This accomplishes the same reliability goals a different way, i.e. strives to maintain the same level of risk. Unfortunately, the time extension is generally large and a design change is often a better solution if it is possible.

(b) Tailoring of Configurations - One of the most effective assembly level tests is the thermal-vacuum test which provides a good approximation of the temperature distribution for most assemblies. For some assemblies, particularly those with low power dissipating components and with few mechanical illtelhlcestlc'lw'cell them and a heat sink, there is little difference in the temperature distributions if the tests are conducted in air rather than vacuum.

For some contractors, thermal vacuum facilities are limited and substituting ambient for vacuum tests can represent a savings in time or costs. A JPL tailoring guideline for this substitution[9] calls for an analysis to show that the temperature distribution is not significantly altered by the ambient test conditions. However, depending on the design details, there may be an additional risk incurred because the analysis itself is not verified by test. Because of this, assemblies with high power dissipating components or If. components are generally thermally tested only under vacuum conditions.

(c) Tailoring of Test Techniques - Research for improved testing techniques is a continuing activity. In the area of improving the simulation of the launch environment, a significant improvement has been developed for controlling vibration tests. Traditionally, the launch environment has been simulated with vibration tests designed to bracket, with a margin, the measured acceleration levels of previous launches of the same launch vehicle or carrier. A new method using force limiting as an additional control parameter is now being used at JPL.[10]

One of the difficulties of the acceleration-controlled approach is the significant difference in the dynamic impedance between a shaker and the actual flight interface. Sometimes elaborate fixturing is used to partially compensate for this mismatch in mass and stiffness, but often this just transfers the problem form the spacecraft-shaker interface to the spacecraft-fixture interface.

In recent years, force gages have been improved and are now available for measuring flight interface forces and for controlling vibration tests. These force-limiting test control methods are currently implemented as tailoring guidelines primarily because of the limited amount of flight measurements. With more general usage and flight experience they are destined to be adopted as revised or alternate standards. This example of tailoring is not so much an outfitting of a project with a custom product assurance test program as it is a means of transitioning to a new standard.

[8] Ibid, pg. 1, RTG-001 entitled Level and Duration of the Assembly Level Thermal Vacuum Test for Electronic Assemblies, February 1994.

[9] Ibid, pg. 14, RTG-002 entitled Thermal Vacuum vs. Temperature Atmospheric Tests of Flight Electronics Assemblies, January 1994.

Conclusions

This paper on strategies for tailoring spacecraft test standards has both advocated for and cautioned against tailoring. Applied sensibly and carefully, tailoring can improve the test effectiveness and relax constraints on certain project resources, including weight, power, cost, and schedule time. On the other hand, tailoring a product assurance program usually incurres some element of risk and may cost more simply because of the departure from the standardized documentation, familiar procedures, and available facilities.

The rate of equipment failures typically has not leveled off during the first three years after launch. This suggests that improvements in the pre-launch tests programs are needed. With schedule and costs increasingly constrained in the development of space hardware, tailoring test programs to specific project needs and resources becomes essential. The strategy presented is not unique but serves as a model for a systematic determination of tailor-made test programs.

[10] Ibid, pg.22, RTG-003 entitled Guidelines for Tailoring Vibration Tests Using Force Limiting, March 1994.